Energy Conversion and Management 91 (2015) 132–139

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Advanced exergoeconomic analysis of a gas engine heat pump (GEHP) for food drying processes

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ARTICLE INFO

Article history:
Received 4 August 2014
Accepted 14 November 2014
Available online 18 December 2014

Keywords:
Advanced exergoeconomic analysis
Exergy
Drying
Gas-engine driven heat pump

ABSTRACT

Exergetic and exergoeconomic analyses are often used to evaluate the performance of energy systems from the thermodynamic and economic points of view. While a conventional exergetic analysis can be used to recognize the sources of inefficiencies, the so-called advanced exergy-based analysis is convenient for identifying the real potential for thermodynamic improvements and the system component interactions by splitting the exergy destruction and the total operating cost within each component into endogenous/exogenous and unavoidable/avoidable parts. In this study for the first time an advanced exergoeconomic analysis is applied to a gas-engine-driven heat pump (GEHP) drying system used in food drying for evaluating its performance along with each component. The advanced exergoeconomic analysis shows that the unavoidable part of the exergy destruction cost rate within the components of the system is lower than the avoidable part. The most important components based on the total avoidable costs are drying ducts, the condenser and the expansion valve. The inefficiencies within the condenser could particularly be improved by structural improvements of the whole system and the remaining system components. Finally, it can be concluded that the internal design changes play a more essential role in determining the cost of each component.

1. Introduction

Heat pump (HP) systems are known to be energy efficient devices when used in drying processes. Their ability to convert the latent heat of condensation into sensible heat at the hot gas condenser makes them unique in drying applications. Further, their ability to produce well-controlled drying conditions is particularly important to drying high-valued quality products [1]. Therefore, many studies focused on the food drying applications of HPs [2–10]. HPs are divided into many categories according to the energy source, namely electric-driven HPs (EHPs), chemical HPs, ground source HPs, geothermal energy HPs, solar-energy-assisted HPs, and gas-engine-driven HPs (GEHPs) [11]. A GEHP system is a new HP system (one of today's promising new technologies) and usually consists of two parts: a heat pump system and a gas engine. The operating cycle of a heat pump system is the same as that for a vapor compression refrigeration cycle with the main components being the evaporator, compressor, condenser, and expansion valve. An internal combustion gas engine is used to drive the compressor instead of an electric motor [12]. Many investigators have focused on GEHPs used for air conditioning, operational control, and few of them have considered water cooling or heating applications [13–18].

The exergy-based performance evaluation and subsequent optimization of drying facilities have been of particular interest for various researchers in recent years. It is noteworthy that the strategies suggested by the exergy concept or by an energy analysis to improve the system efficiency are quite different. The main objective of exergy analysis of drying systems is to provide a clear picture of the process, to quantify the sources of inefficiency, to distinguish the quality of energy consumption, to select optimal drying conditions and to reduce the environmental impact of drying systems [19]. An energy conversion system should be analyzed using the exergy concept to determine the inefficiencies within it. Conventional exergy-based analyses are powerful tools for conducting such an analysis. However, a conventional exergy-based analysis provides us with information only about the location and magnitude of the inefficiencies; a conventional analysis does

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http://dx.doi.org/10.1016/j.enconman.2014.11.044
0196-8904/

Nomenclature

$\dot{E}x$	exergy flow rate (kW)
c	unit exergy cost ($/GJ)
$\dot{C}$	cost rate associated with an exergy stream ($/h)
f	exergoeconomic factor (%)
r	relative cost difference
T	temperature (K)
$\dot{Z}$	cost rate associated with capital investment ($/h)
Subscripts	
D	exergy destruction
F	fuel exergy
P	product exergy
k	kth component
Superscripts	
AV	avoidable
AV,EN	avoidable endogenous
AV,EX	avoidable exogenous
EN	endogenous
EX	exogenous
UN	unavoidable
UN,EN	unavoidable endogenous
UN,EX	unavoidable exogenous
Greek letters	
Δ	difference
ε	exergetic (second-law) efficiency (%)
Abbreviations	
DC	drying chamber
DPHE	double pipe heat exchanger
EAHE	exhaust air heat exchanger
GE	gas engine
GEHP	gas engine driven heat pump
HP	heat pump
PEC	purchased equipment cost

not provide information about the relationships among the components, nor does it provide sufficient information about real improvement strategies. Thus, to reduce the deficiencies of a conventional exergy analysis, the so-called advanced exergy based methods were developed by Tsatsaronis and coworkers [19–29].

An advanced exergy-based method that involves the endogenous and exogenous concepts was proposed for further splitting the avoidable and unavoidable exergy destruction and the total operating cost (the sum of both the exergy destruction cost and the investment cost) into four parts [22–24]. The exergy destruction, the exergy costs and the investment for any system component are, in general, affected by the component itself and by other components of the same system. An advanced exergy-based analysis simultaneously provides engineers with information about the limits of improvement of the considered component or the overall system, which resulted from technical or ecological constraints. In other words, exergy destructions (or a part of them) may be unavoidable due to present technical limitations, while another part may be caused by the exergy destruction occurring within the other components of the same system. Through an advanced exergy-based analysis, the potential for improvement for each component in the overall system can be estimated [23]. An advanced exergy analysis has the capability to determine, which part of the inefficiencies is caused by component interactions, and which part can be avoided through technological improvements of a plant. The exergy destructions are split into two main groups, namely (i) endogenous–exogenous exergy destructions, and (ii) avoidable–unavoidable exergy destructions [23,25].

In the literature, there is a limited number of papers related to advanced exergy- and exergoeconomic-based analyses of energy conversion systems [22–34].

Morosuk and Tsatsaronis [26] demonstrated the application of a detailed advanced exergetic analysis to a novel cogeneration system. They identified the improvement potentials and the interactions among the components. Boyano et al. [27] investigated the environmental aspects of a steam methane reformer technology and highlighted the potential for improving the reformer through a conventional and an advanced exergoenvironmental analysis. In Ref. [24], the potential for energy savings in distillation processes is identified using the concepts of avoidable and unavoidable exergy destruction and investment costs as a part of exergy analysis and exergoeconomic evaluation. In addition, a methodology to calculate the avoidable and unavoidable exergy destruction and investment costs is proposed. Morosuk et al. [28] analyzed a liquefied-natural-gas regasification plant, which produces electricity, using advanced exergy and advanced exergoenvironmental methods. Petrakopoulou et al. [29] investigated a combined power plant using advanced exergy and advanced exergoenvironmental analyses to improve the system. Petrakopoulou et al. [30] evaluated a complex combined-cycle power plant with CO_2 capture using an advanced exergoeconomic analysis. Hepbasli and Kecebas [31] applied an advanced exergy approach to a geothermal district heating heat pump system, and in [32] to a trigeneration system using a diesel–gas engine. Acikkalp et al. [33] used advanced exergy and advanced exergoeconomic analyses to evaluate an electricity generation facility. Vučković et al. [34] investigated the performance of critical components and the potential for efficiency improvement of a complex industrial energy supply plant using an advanced exergy analysis. In all studies in the literature, where an advanced exergy-based method has been applied, the most important system components and their interactions have been identified, and options for improving the overall systems have been revealed.

In the open literature, only one study, which has been recently performed by the authors [35], on the advanced exergetic analysis of a GEHP system exists, but no studies on advanced exergoeconomic analysis of GEHPs have yet been published. The above presented aspects provide the primary motivation behind performing the present study with the objectives of (i) applying advanced exergoeconomic analysis to a GEHP drying system and evaluating its performance, (ii) comparing the results obtained by the conventional and the advanced exergoeconomic analyses, and (iii) discussing the performance and possible improvements for the overall system.

2. System description and drying procedure

Three different medicinal and aromatic plants, *Foeniculum vulgare*, *Malva sylvestris* L. and *Thymus vulgaris*, were dried in a pilot scale GEHP belt conveyor drier. This drying system was designed and constructed in the Department of Mechanical Engineering, Faculty of Engineering, Ege University, Izmir, Turkey for a research project. Fig. 1 illustrates a schematic diagram of the GEHP drying system, which consists of two parts, the GEHP, and the drying chamber (DC). Also the GEHP system, which is driven by a gas-fuelled internal combustion engine instead of an electric motor,

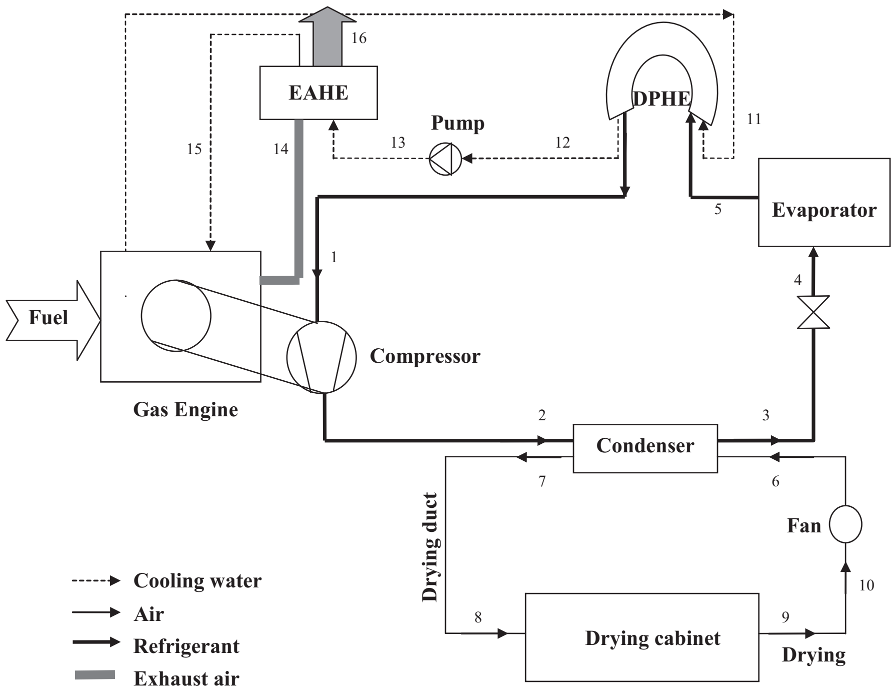

Fig. 1. A schematic illustration of the components of the GEHP drying system and streams (modified from Gungor et al. [35]).

has two main parts: (i) a HP system (consisting of a compressor, a condenser, an expansion valve and an evaporator), and (ii) a gas engine (GE). Air is heated by the GEHP system and its temperature is controlled by a control unit. R407C was used as the refrigerant in the GEHP system. The drying air velocity was adjusted by a fan and its speed control unit, and the drying air was recycled. The dimensions of the compartment are 3.0 m × 1.0 m × 1.0 m. Measurements were performed to determine the exergetic efficiency of the system during the drying process. Before starting the experiments, the system was run for at least 1 h to obtain steady-state conditions. Fresh plant samples were spread onto the belt conveyor as a thin layer. Medicinal and aromatic plants were dried for their valuable components, which are heat sensitive, so drying experiments were carried out at a drying air temperature of 45 °C with a drying air velocity of 1 m/s. Humidities, temperatures and velocities were measured in the drying chamber with robust humidity probes (Testo, 0636.2140, Freiburg, Germany), vane/temperature probes (Testo, 0635.9540, Freiburg, Germany) and professional telescopic handle for plug-in vane probes (Testo, 0430.0941, Freiburg, Germany) respectively. Measurements of the drying air temperature, velocity and relative humidity were recorded every 15 min. A digital balance (Scaltec SBA 61, Goettingen, Germany) was used to measure the weight loss of the sample during drying experiments. The ambient temperature and the relative humidity were also measured and recorded. Pressures and temperatures of the refrigerant were measured with pressure probes (Testo, low/high-pressure probes, 0638.01941, Freiburg, Germany) and surface temperature probes (Testo, temperature probes, 0628.0019, Freiburg, Germany), respectively. All measured values were observed and recorded simultaneously with a multi-function instrument (Testo 350-XL/454, control unit, Freiburg, Germany) and loggers.

3. Methodology

Conventional exergy-based methods pinpoint components and processes with high irreversibilities. However, they lack certain insight. It is, therefore, important to understand how exergy is destroyed in a process or a component. In the so-called advanced exergy-based methods, the exergy destruction, the cost of exergy destruction, and the investment cost rates are split into endogenous/exogenous and avoidable/unavoidable parts. The role of advanced exergy-based analyses is (a) to reveal avoidable thermodynamic inefficiencies, costs, and environmental impacts that show the potential for improvement of a component/process, and (b) to calculate the magnitude of internal or external thermodynamic inefficiencies, costs and environmental impacts that show how strongly the components of a system influence one another. The final goal when using such methods is to improve a process or a component through the implementation of changes pinpointed by the results of the advanced analyses [36]. The application of advanced exergy-based methods requires carefully defined steps that use as input results from conventional exergy-based analyses. This means that conventional exergy and exergoeconomic analyses must be performed before the advanced exergy and exergoeconomic analyses are conducted.

In this study an advanced exergoeconomic analysis is used to separate the component-related costs (investment, operating, and maintenance costs, $\dot{Z}$) and the costs associated with exergy destruction, $\dot{C}_D$, into avoidable/unavoidable (*AV/UN*), endogenous/exogenous (*EN/EX*) and their combined parts (e.g., avoidable exogenous, *AV EX* and avoidable endogenous, *AV EN*). The equations used to perform the conventional exergoeconomic analysis and advanced exergoeconomic analysis for the GEHP drying system can be found in Table 1 [37].

To calculate the endogenous/exogenous costs, the investment costs and the costs of exergy destruction of each component are split into costs associated with the operation of the component itself (endogenous) and the part of the cost related to the thermodynamic inefficiencies of other components in the system (exogenous). The endogenous part is associated only with the costs occurring within the *k*th component when all other components operate theoretically and the component being considered operates with its real efficiency. The exogenous part is calculated by subtracting the endogenous part from the total real investment cost and the real cost of exergy destruction for each component.

Table 1
Equations used for conventional exergetic/exergoeconomic and advanced exergoeconomic analysis.

Conventional exergetic/exergoeconomic analysis		Advanced exergoeconomic analysis		
Parameters	Equations	Parameters	Equations	
Exergy balance	$\dot{E}x_{D,k} = \dot{E}x_{F,k} - \dot{E}x_{P,k}$	*EN*	$\dot{Z}_k^{EN} = \dot{E}x_{P,k}^{EN}\left(\frac{\dot{Z}}{\dot{E}x_P}\right)_k^{real}$	$\dot{C}_{D,k}^{EN} = c_{F,k}\dot{E}x_{D,k}^{EN}$
Efficiency	$\varepsilon_k = \frac{\dot{E}x_{P,k}}{\dot{E}x_{F,k}} = 1 - \frac{\dot{E}x_{D,k}}{\dot{E}x_{F,k}}$	*EX*	$\dot{Z}_k^{EX} = \dot{Z}_k^{real} - \dot{Z}_k^{EN}$	$\dot{C}_{D,k}^{EX} = \dot{C}_{D,k}^{real} - \dot{C}_{D,k}^{EN}$
Exergy destruction cost rate	$\dot{C}_{D,k} = c_{F,k}\dot{E}x_{D,k}$	*UN*	$\dot{Z}_k^{UN} = \left(\frac{PEC^{UN}}{PEC^{real}}\right)_k X\dot{Z}_k^{real}$	$\dot{C}_{D,k}^{UN} = c_{F,k}\dot{E}x_{D,k}^{UN}$
Exergoeconomic factor	$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}}$	*AV*	$\dot{Z}_k^{AV} = \dot{Z}_k^{real} - \dot{Z}_k^{UN}$	$\dot{C}_{D,k}^{AV} = \dot{C}_{D,k}^{real} - \dot{C}_{D,k}^{UN}$
		UN EN, UN EX	$\dot{Z}_k^{UN,EN} = \dot{E}x_{P,k}^{EN}\left(\frac{\dot{Z}_k^{UN}}{\dot{E}x_P}\right)_k$	$\dot{C}_{D,k}^{UN,EN} = c_{F,k}\dot{E}x_{D,k}^{UN,EN}$
			$\dot{Z}_k^{UN,EX} = \dot{Z}_k^{UN} - \dot{Z}_k^{UN,EN}$	$\dot{C}_{D,k}^{UN,EX} = \dot{C}_{D,k}^{UN} - \dot{C}_{D,k}^{UN,EN}$
Relative cost difference	$r = \frac{c_{P,k} - c_{F,k}}{c_{F,k}}$	*AV EN, AV EX*	$\dot{Z}_k^{AV,EN} = \dot{Z}_k^{EN} - \dot{Z}_k^{UN,EN}$	$\dot{C}_{D,k}^{AV,EN} = \dot{C}_{D,k}^{EN} - \dot{C}_{D,k}^{UN,EN}$
			$\dot{Z}_k^{AV,EX} = \dot{Z}_k^{EX} - \dot{Z}_k^{UN,EX}$	$\dot{C}_{D,k}^{AV,EX} = \dot{C}_{D,k}^{EX} - \dot{C}_{D,k}^{UN,EX}$

Table 2
Assumptions for the calculation of the unavoidable investment cost rates.

Component	$\dot{Z}_k^{UN}$ (operating conditions or % $\dot{Z}_k^{real}$)
Compressor	85%
Condenser	$\Delta T_{\min} = 287$ K, $\Delta P_{UN} = \Delta P_{real}$
Expansion valve	100%
Evaporator	$\Delta T_{\min} = 276$ K, $\Delta P_{UN} = \Delta P_{real}$
DPHE	$\Delta T_{\min} = 300$ K, $\Delta P_{UN} = \Delta P_{real}$
Drying cabinet	90%
Drying ducts	90%

Moreover, a realistic potential for economically improving the kth component can be assessed by splitting the exergy destruction cost rate and the investment cost rate within each system component into its unavoidable and avoidable parts, depending on whether the costs can be avoided or not. As seen in Table 1, the calculation of the unavoidable exergy destruction cost combines results from the conventional exergoeconomic and the advanced exergetic analyses. The unavoidable exergy destruction rate $\left(\dot{E}x_{D,k}^{UN}\right)$ for the kth component is first obtained with the exergy product rate in the real process. The unavoidable cost rate associated with the exergy destruction rate and the unavoidable investment cost rate $\left(\dot{Z}_k^{UN}\right)$ are then found using the equations shown in Table 1. When subtracting the unavoidable costs from the total costs, we calculate the avoidable costs. To perform the simulations required to calculate the avoidable/unavoidable investment costs, the operating conditions shown in Table 2 have been assumed. For better understanding the costs related to the internal operating conditions and the component interactions, the unavoidable exogenous and the avoidable exogenous parts within the kth component are split accordingly.

4. Results and discussion

The main results obtained from the conventional exergetic and exergoeconomic analyses of the GEHP system are shown in Table 3 while the assumptions made for calculating the avoidable/unavoidable investment costs are listed in Table 2. According to Ref. [35], the exergy efficiency of the overall system was determined to be in the range of 79.7–81.7%. The exergy destruction rate of 3.336–3.729 kW accounted for 18.0–20.0% of the total exergy input (exergetic fuel) rate while the total exergetic product rate was 22.4–25.0%. The highest exergy destruction rate was caused in the drying ducts (in need of improvement), followed by the destruction rates within the condenser and the expansion valve. The exergy destructions within the evaporator and drying cabinet are relatively low. Therefore, these components cannot significantly affect the efficiency of the overall system. The exergoeconomic factor supplies information about the relationship between the investment costs and the costs of inefficiencies of the system components. A large exergoeconomic factor implies that the investment costs should be decreased to decrease the system costs, whereas a small factor implies that more energy-efficient equipment should be used to decrease the system costs. The system investigation shows that the drying cabinet has the maximum exergoeconomic factor (62.6–66.9%), whereas the drying ducts have the minimum exergoeconomic factor (3.3–3.9%). The relative cost difference describes the relative increase in the exergy product cost compared to the fuel exergy cost for a component, and this difference has an important role to optimize and evaluate the system component. According to the conventional exergoeconomic analysis (Table 3), the largest relative cost difference occurs in the fan (3.77–4.73), the DPHE (1.65–4.24) and the drying ducts (0.80–1.08), respectively. The drying ducts (1632.39 \$/GJ) and the condenser (1075.23 \$/GJ) have relatively high fuel cost rates compare to the expansion valve (313.30 \$/GJ) and the evaporator (355.85 \$/GJ) in the drying process of *Malva sylvestris L.* Moreover, an important result of the exergoeconomic analysis is the correlation of exergy destruction rate with costs. The exergy destruction cost rate is calculated at the component level, and compared to the respective investment cost rates. The components are then evaluated based on their total operating cost rate $(\dot{C}_{D,k} + \dot{Z}_k)$, which consists of their investment and exergy destruction cost rates. The higher this total operating cost rate, the higher the influence of the component on the costs associated with the overall system and thus, the more significant the component. As can be seen in Table 3, the highest total operating cost is associated with the drying ducts, followed by the condenser, the drying cabinet, the compressor, the expansion valve, the DPHE and the fan, respectively. For example, because of the low contribution of the investment cost to the total operating cost of the drying duct and its high relative cost difference (r_k), we conclude that this component can be improved by reducing the exergy being destroyed within it. Also, the exergoeconomic factor ((f_k)) of the drying ducts are low. Therefore, also from the low values of the f_k, we obtain the recommendation, that a reduction in the exergy destruction should be considered, even if this would increase the investment cost of the drying ducts. The detailed results and assumptions from the advanced exergoeconomic analysis are shown in Tables 4–9.

Tables 4–6 present the results from the splitting the investment costs of the system components for drying of three different medicinal and aromatic plants. The endogenous investment cost rate, $\dot{Z}_k^{EN}$ is higher than the exogenous rate, $\dot{Z}_k^{EX}$, for all

Table 3
Results obtained from the conventional exergetic and exergoeconomic analysis.

Component	$\dot{E}x_{D,k}$ (kW)			ε (%)			c_F ($/GJ)			f (%)			r			$\dot{C}_{D,k}+\dot{Z}_k$ ($/h)		
	1[a]	2[b]	3[c]	1[a]	2[b]	3[c]	1[a]	2[b]	3[c]	1[a]	2[b]	3[c]	1[a]	2[b]	3[c]	1[a]	2[b]	3[c]
Compressor	0.231	0.218	0.274	90.28	91.05	88.33	713.56	672.80	1061.19	22.32	24.46	14.00	0.14	0.13	0.15	0.76	0.70	1.22
Condenser	0.617	0.629	0.515	71.45	72.02	71.53	1075.23	990.79	1397.94	5.89	6.24	6.76	0.42	0.41	0.31	2.54	2.40	2.21
Expansion valve	0.592	0.599	0.723	88.40	88.88	85.87	313.30	303.48	669.56	4.87	4.96	1.92	0.14	0.13	0.17	0.70	0.68	1.77
Evaporator	0.070	0.181	0.205	85.99	72.38	62.18	355.85	343.48	782.11	58.69	36.41	18.17	0.40	0.60	0.74	0.36	0.35	0.70
DPHE	0.256	0.423	0.490	40.31	27.24	19.53	370.72	342.88	779.28	10.12	6.86	2.72	1.65	2.87	4.24	0.38	0.56	1.41
Fan	0.043	0.046	0.047	24.95	26.06	27.14	734.83	668.65	791.82	34.15	35.08	30.87	4.73	4.43	3.77	0.17	0.17	0.19
Drying ducts	1.447	1.494	1.191	72.30	71.50	75.18	1632.39	1499.40	1784.33	3.55	3.87	3.33	1.01	1.08	0.80	4.58	4.38	4.09
Drying cabinet	0.110	0.140	0.120	95.61	94.44	94.73	809.56	735.29	886.73	66.86	63.37	62.59	0.14	0.16	0.15	0.96	1.01	1.02

[a] The results for drying of *Malva sylvestris* L.
[b] The results for drying of *Foeniculum vulgare*.
[c] The results for drying of *Thymus vulgaris*.

Table 4
Splitting the investment cost rates for drying of *Malva sylvestris* L. ($/h).

	$\dot{Z}_k^{real}$	$\dot{Z}_k^{UN}$	$\dot{Z}_k^{AV}$	$\dot{Z}_k^{EN}$	$\dot{Z}_k^{EX}$	$\dot{Z}_k^{AV}$		$\dot{Z}_k^{UN}$	
						$\dot{Z}_k^{AV,EN}$	$\dot{Z}_k^{AV,EX}$	$\dot{Z}_k^{UN,EN}$	$\dot{Z}_k^{UN,EX}$
Compressor	0.171	0.145	0.026	0.138	0.033	0.021	0.005	0.117	0.028
Condenser	0.150	0.135	0.015	0.143	0.007	0.014	0.001	0.129	0.006
Expansion valve	0.035	0.030	0.005	0.028	0.007	0.003	0.002	0.025	0.005
Evaporator	0.128	0.115	0.013	0.088	0.040	0.009	0.004	0.080	0.035
DPHE	0.038	0.034	0.004	0.028	0.010	0.003	0.001	0.025	0.009
Fan	0.060	0.036	0.024	0.043	0.017	0.017	0.007	0.026	0.010
Drying ducts	0.043	0.038	0.005	0.029	0.014	0.003	0.002	0.026	0.012
Drying cabinet	0.641	0.577	0.064	0.415	0.226	0.041	0.023	0.374	0.203

Table 5
Splitting the investment cost rates for drying of *Foeniculum vulgare* ($/h).

	$\dot{Z}_k^{real}$	$\dot{Z}_k^{UN}$	$\dot{Z}_k^{AV}$	$\dot{Z}_k^{EN}$	$\dot{Z}_k^{EX}$	$\dot{Z}_k^{AV}$		$\dot{Z}_k^{UN}$	
						$\dot{Z}_k^{AV,EN}$	$\dot{Z}_k^{AV,EX}$	$\dot{Z}_k^{UN,EN}$	$\dot{Z}_k^{UN,EX}$
Compressor	0.171	0.145	0.026	0.136	0.035	0.020	0.006	0.115	0.030
Condenser	0.150	0.135	0.015	0.143	0.007	0.014	0.001	0.129	0.006
Expansion valve	0.035	0.031	0.004	0.024	0.011	0.003	0.001	0.021	0.010
Evaporator	0.128	0.115	0.013	0.094	0.034	0.009	0.004	0.084	0.031
DPHE	0.039	0.035	0.004	0.032	0.007	0.003	0.001	0.029	0.006
Fan	0.060	0.036	0.024	0.045	0.015	0.018	0.006	0.027	0.009
Drying ducts	0.043	0.038	0.005	0.031	0.012	0.003	0.002	0.028	0.010
Drying cabinet	0.641	0.577	0.064	0.435	0.206	0.044	0.020	0.391	0.186

Table 6
Splitting the investment cost rates for drying of *Thymus vulgaris* ($/h).

	$\dot{Z}_k^{real}$	$\dot{Z}_k^{UN}$	$\dot{Z}_k^{AV}$	$\dot{Z}_k^{EN}$	$\dot{Z}_k^{EX}$	$\dot{Z}_k^{AV}$		$\dot{Z}_k^{UN}$	
						$\dot{Z}_k^{AV,EN}$	$\dot{Z}_k^{AV,EX}$	$\dot{Z}_k^{UN,EN}$	$\dot{Z}_k^{UN,EX}$
Compressor	0.171	0.145	0.026	0.143	0.028	0.021	0.005	0.121	0.024
Condenser	0.150	0.135	0.015	0.140	0.010	0.014	0.001	0.126	0.009
Expansion valve	0.035	0.031	0.004	0.023	0.012	0.002	0.002	0.020	0.011
Evaporator	0.128	0.115	0.013	0.108	0.020	0.011	0.002	0.097	0.018
DPHE	0.039	0.035	0.004	0.028	0.011	0.003	0.001	0.026	0.009
Fan	0.060	0.036	0.024	0.037	0.023	0.015	0.009	0.022	0.014
Drying ducts	0.043	0.038	0.005	0.030	0.013	0.004	0.001	0.026	0.012
Drying cabinet	0.641	0.577	0.064	0.418	0.223	0.042	0.022	0.376	0.201

system components. This shows, in general, that the interactions among components do not affect significantly the investment costs. In particular, 80% and 93–95% of the investment cost of the compressor and condenser, respectively, is endogenous, i.e., the investment costs of these components are mainly affected by internal thermodynamic inefficiencies and much less by the structure of the system and the operation of the remaining components. For example the compressor has endogenous investment costs four times higher than the corresponding exogenous values. On the other hand, the difference between the endogenous and exogenous costs of the evaporator is rather small.

Table 7
Results from splitting the exergy destruction cost rates for drying of *Malva sylvestris* L. ($/h).

	$\dot{C}_{D,k}^{real}$	$\dot{C}_{D,k}^{AV}$	$\dot{C}_{D,k}^{UN}$	$\dot{C}_{D,k}^{EN}$	$\dot{C}_{D,k}^{EX}$	$\dot{C}_{D,k}^{AV}$		$\dot{C}_{D,k}^{UN}$	
						$\dot{C}_{D,k}^{AV,EN}$	$\dot{C}_{D,k}^{AV,EX}$	$\dot{C}_{D,k}^{UN,EN}$	$\dot{C}_{D,k}^{UN,EX}$
Compressor	0.595	0.253	0.342	0.550	0.045	0.241	0.012	0.308	0.034
Condenser	2.388	2.357	0.031	0.445	1.943	0.418	1.939	0.027	0.004
Expansion valve	0.666	0.521	0.145	0.663	0.003	0.521	0	0.140	0.005
Evaporator	0.235	0.171	0.064	0.172	0.063	0.141	0.030	0.031	0.033
DPHE	0.342	0.180	0.162	0.307	0.035	0.176	0.004	0.131	0.031
Fan	0.116	0.042	0.074	0.066	0.050	0	0.042	0.067	0.007
Drying ducts	4.545	3.342	1.203	2.635	1.910	1.502	1.840	1.134	0.069
Drying cabinet	0.318	0.085	0.233	0.154	0.164	0.003	0.082	0.151	0.082

Table 8
Results from splitting the exergy destruction cost rates for drying of *Foeniculum vulgare* ($/h).

	$\dot{C}_{D,k}^{real}$	$\dot{C}_{D,k}^{AV}$	$\dot{C}_{D,k}^{UN}$	$\dot{C}_{D,k}^{EN}$	$\dot{C}_{D,k}^{EX}$	$\dot{C}_{D,k}^{AV}$		$\dot{C}_{D,k}^{UN}$	
						$\dot{C}_{D,k}^{AV,EN}$	$\dot{C}_{D,k}^{AV,EX}$	$\dot{C}_{D,k}^{UN,EN}$	$\dot{C}_{D,k}^{UN,EX}$
Compressor	0.528	0.066	0.462	0.438	0.090	0.022	0.044	0.416	0.046
Condenser	2.247	2.175	0.072	0.360	1.887	0.297	1.878	0.062	0.010
Expansion valve	0.654	0.508	0.146	0.608	0.046	0.487	0.021	0.121	0.025
Evaporator	0.224	0.029	0.195	0.162	0.062	0.023	0.006	0.138	0.057
DPHE	0.522	0.332	0.190	0.474	0.048	0.323	0.009	0.150	0.040
Fan	0.110	0.055	0.055	0.069	0.041	0.019	0.036	0.050	0.005
Drying ducts	4.341	3.228	1.113	2.551	1.790	1.502	1.726	1.050	0.063
Drying cabinet	0.371	0.138	0.233	0.196	0.175	0.038	0.100	0.158	0.075

Table 9
Results from splitting the exergy destruction cost rates for drying of *Thymus vulgaris* ($/h).

	$\dot{C}_{D,k}^{real}$	$\dot{C}_{D,k}^{AV}$	$\dot{C}_{D,k}^{UN}$	$\dot{C}_{D,k}^{EN}$	$\dot{C}_{D,k}^{EX}$	$\dot{C}_{D,k}^{AV}$		$\dot{C}_{D,k}^{UN}$	
						$\dot{C}_{D,k}^{AV,EN}$	$\dot{C}_{D,k}^{AV,EX}$	$\dot{C}_{D,k}^{UN,EN}$	$\dot{C}_{D,k}^{UN,EX}$
Compressor	1.050	0.557	0.492	0.596	0.454	0.138	0.419	0.458	0.034
Condenser	2.063	2.023	0.040	0.176	1.887	0.146	1.877	0.030	0.010
Expansion valve	1.742	1.497	0.245	1.696	0.046	1.461	0.036	0.235	0.010
Evaporator	0.577	0.301	0.276	0.422	0.155	0.236	0.065	0.186	0.090
DPHE	1.375	1.268	0.107	1.111	0.264	1.027	0.241	0.084	0.023
Fan	0.134	0.037	0.097	0.106	0.028	0.016	0.021	0.090	0.007
Drying ducts	4.050	2.730	1.320	2.466	1.584	1.216	1.514	1.249	0.071
Drying cabinet	0.383	0.121	0.262	0.185	0.198	0.015	0.106	0.170	0.092

The differences between the endogenous and exogenous investment costs decrease significantly when we consider the avoidable parts of the endogenous/exogenous costs. Here interesting results are found for the condenser, the avoidable endogenous cost of which decreases to approximately that of the expansion valve, while its avoidable exogenous cost is surpassed by that of other system components. The improvement potential for the investment cost of the system was found to be low, because the unavoidable parts of the components are higher than the avoidable parts. The high avoidable endogenous investment cost of the GEHP system show that if we wanted to decrease this cost for a component, changes should relate to the component itself. This could be, for example, by replacing the construction materials or the manufacturing techniques with less expensive ones, when the operating conditions allow it. Based on the evaluation of the results of the sources of the investment cost, the system can potentially be improved by improving the drying cabinet, compressor and condenser, in this order. In this case, the component with the highest avoidable endogenous cost rate of investment (0.044 $/h) is the drying cabinet.

The results from splitting the cost rates of exergy destruction for the drying of three different medicinal and aromatic plants are given in Tables 7–9 and show that the endogenous exergy destruction cost rates are larger than the exogenous exergy destruction cost rates for all components except for the condenser and drying cabinet. This result indicates that the latter are affected more strongly by the other components, and the exergy destruction costs of these components can be reduced by decreasing the exergy destruction of the other components. Measures that could be taken to decrease the cost of exergy destruction may include the replacement of existing components with others of newer and more efficient technology. Nevertheless, although the exogenous costs are of relatively low significance when compared to the endogenous costs, their sources reveal additional improvement potential for the overall system. The maximum endogenous exergy destruction cost rate is in the drying ducts (2.45–2.63 $/h) and it exhibits the highest exergy destruction among all components of the considered overall system. To determine the improvement potential of the exergy destruction cost, the avoidable exergy destruction costs should be examined.

The improvement potentials of the components are indicated by the avoidable part of the exergy destruction cost rates. According to Tables 7–9, the avoidable exergy destruction cost rates are higher than the unavoidable exergy destruction cost rates of the system components except for the compressor and the drying cabinet. This result implies that the system has a high level of

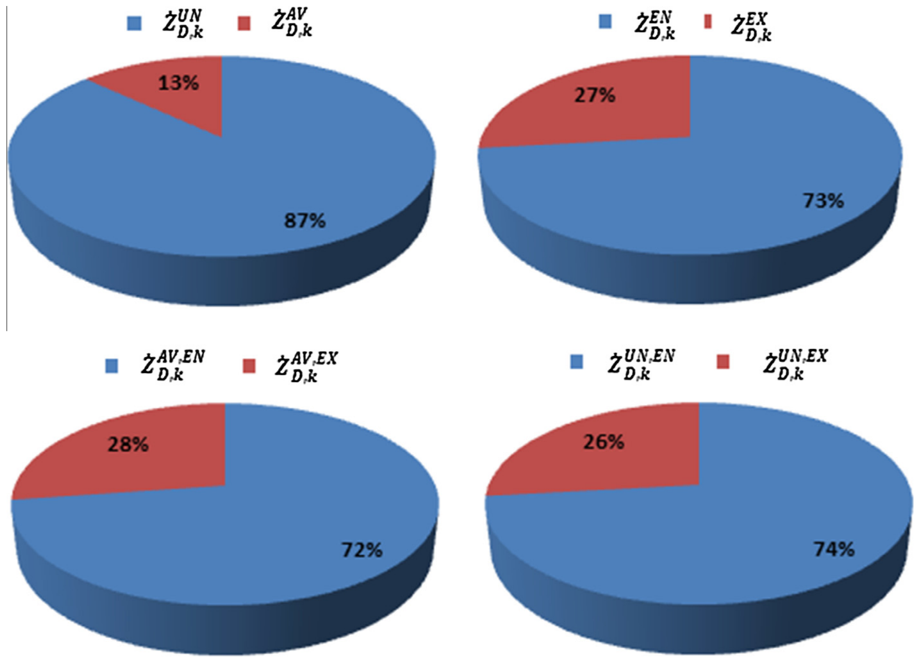

Fig. 2. Investment costs rates results for the overall system.

improvement potential according to the avoidable exergy destruction cost rates. The results from splitting the exergy destruction cost rates into their unavoidable and avoidable parts (Tables 7–9) show that the largest avoidable exergy destruction cost rates occur in the drying ducts (2.73–3.34 $/h), the condenser (2.17–2.55 $/h) and the expansion valve (0.51–1.50 $/h). The data prove that these components handled the largest amount of avoidable exergy destruction cost rates in the overall system. The compressor, drying cabinet and fan have greater unavoidable exergy destruction cost rates than the avoidable ones, which explains why these components have low improvement potential. The drying ducts has the maximum improvement potential (2.73–3.34 $/h), which can be achieved by enhancing the drying efficiency. A large portion of the avoidable exergy destruction cost rate is endogenous (2.47–2.63 $/h), and the remaining part is (1.58–1.91 $/h) is exogenous.

Considering only the conventional exergoeconomic analysis, it can be concluded that the condenser and the drying ducts have large exergy destruction cost rates. However, when evaluating these components using the advanced exergoeconomic analysis, it is shown that 82–9% and 53–5% of their exergy destruction cost rates are avoidable exogenous, respectively. This means that these components are affected by the other components because they have high exogenous exergy destruction rates. For the compressor and the evaporator, the conventional exergoeconomic analysis can be misguiding for the drying of *Malva sylvestris* L. Although they have high exergy destruction cost rates, their improvement potentials are low and are associated with the exergy destruction cost rates of other components. The results of the advanced exergoeconomic analysis of the drying ducts and the compressor show that the analysis must be focused on the components themselves instead of other components. Examining the avoidable exergy destruction cost rates of the system, the percentage of the endogenous and exogenous parts of the avoidable exergy destruction rates are found to be relatively close.

Fig. 2 shows the advanced exergetic parameters for the overall system. Considering the investment cost rates in Fig. 2, the endogenous part of the investment cost rates is notably high (73%), and their improvement potential is notably low (13%). Also, 72% of the investment cost rates is endogenous, which implies that the component interactions are not very strong for the investment cost rates in the system. According to Fig. 2, the endogenous unavoidable parts reach 74% for the system.

5. Conclusions

Within the scope of the present study, we have applied both conventional and advanced exergoeconomic analyses to a GEHP drying system for the first time. We have also separately analyzed the components of the drying system. The main conclusions we have drawn from the results of the present study may be summarized as follows:

- The most important components of the GEHP drying system, in terms of their total avoidable costs (sum of the avoidable investment cost rate and exergy destruction cost rate), are the drying ducts, the condenser, the expansion valve and the compressor. Although the percentages of the avoidable investment cost rates of these components are relatively low, higher percentages were calculated for the avoidable cost of exergy destruction rates of these components.
- The advanced exergoeconomic analysis revealed that the condenser has the highest improvement potential rate, as more than 90% of its total exergy destruction cost rate is avoidable. Contrary to this, the improvement potential of the drying cabinet is low because only 25% of the total exergy destruction cost rate of this component is unavoidable.
- For the investment costs the interactions among components, represented by the exogenous part of the costs, are of lower importance, since for the majority of the components, the endogenous part of the costs is significantly larger for the overall system.
- For the overall system, the improvement potential of the exergy destruction cost rate (avoidable) is determined to be 74% while 55% of this rate is exogenous.

It may be concluded that the conventional exergoeconomic analysis can highlight the main components with high thermodynamic and cost inefficiencies, but cannot consider the interactions

among components or the real potential for improving each component. However, the approach of the advanced exergoeconomic assessment is a more effective tool in identifying the direction and the potential for energy savings in energy systems.

Acknowledgement

The authors are grateful for the financial support provided for the project entitled "Design, test and performance evaluation of a gas engine-driven solar assisted band conveyor heat pump drying system" under Project No: 106M482 by The Scientific and Technological Research Council of Turkey (TUBITAK). They also would like to thank the reviewers for their valuable comments, which have been utilized to improve the quality of the paper.

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